# Resolving the Global Stocktake


K. **Bowman**[3,4] ,N. Bousserez[1,2], D. Henze[1], M. Lee[3], Junjie Liu[3] , Sebastian Eastham[5]

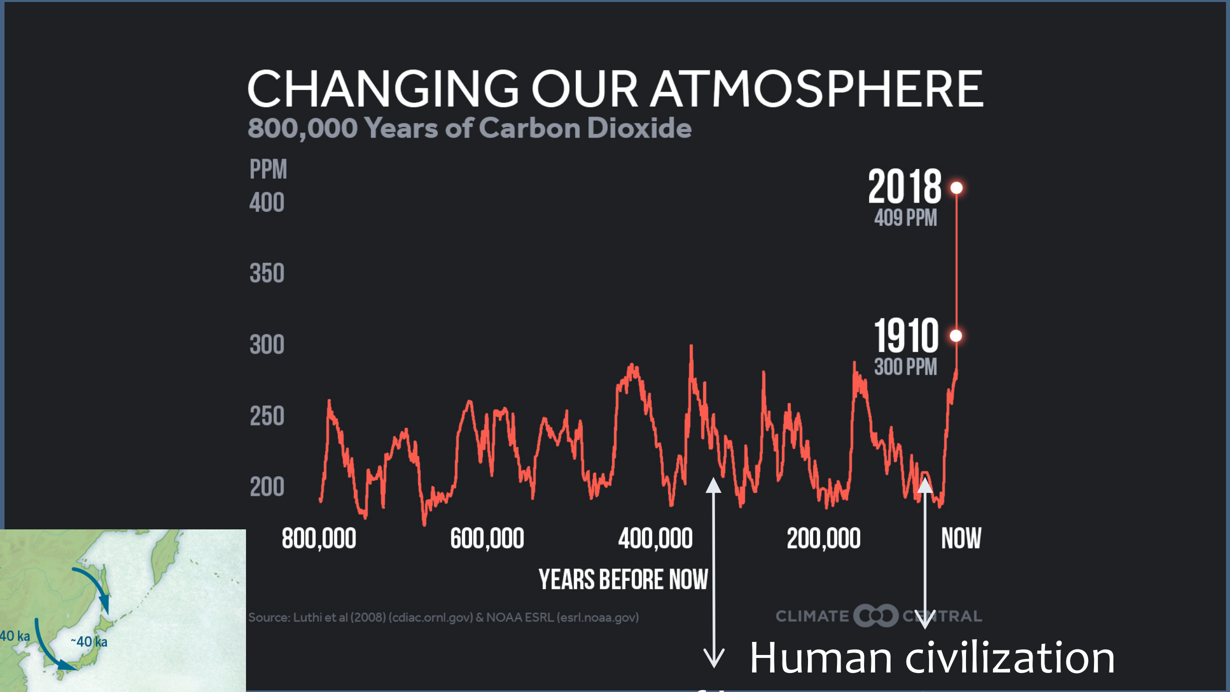
*[1] University of Colorado Boulder, United States,[2] European Centre for Medium-Range Weather Forecasts, United Kingdom,[3] Jet Propulsion Laboratory, California Institute of Technology, United States,[4] Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles, United States*

*[5] Aerospace Engineering, Massachusetts Institute of Technology, Boston, United States*

# A generation like none other

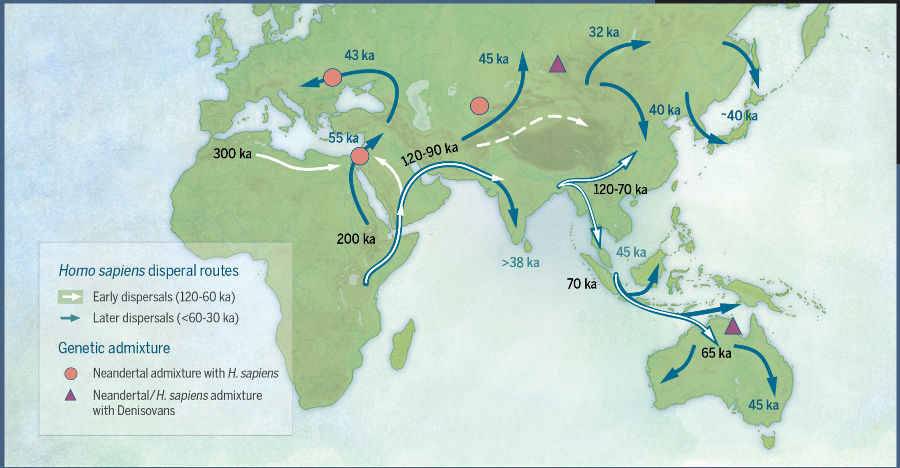
Our ancestors have never experienced this much $CO_2$.

Our progeny will experience a climate like no humans before.



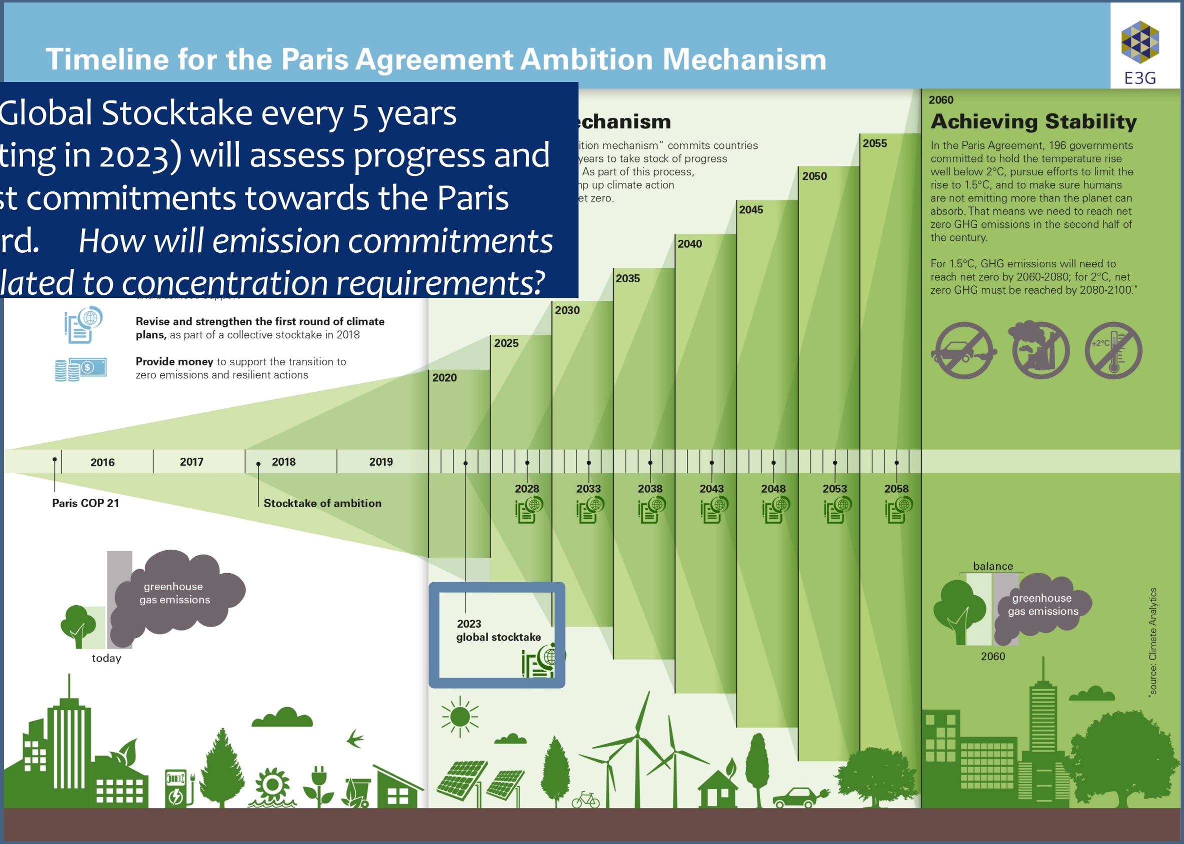

Human civilization

Emergence of homo-sapiens

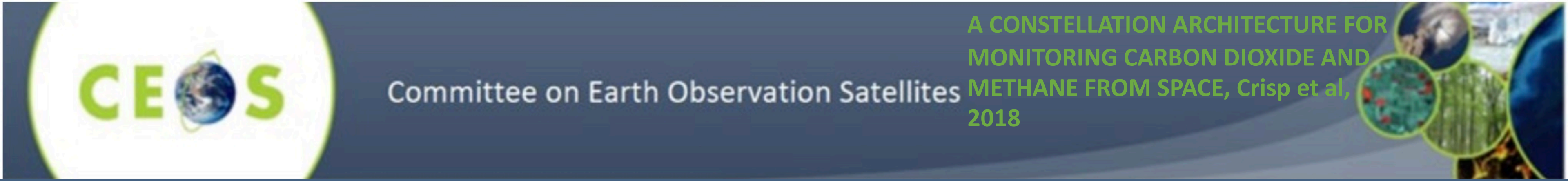


# The Global Stocktake

The  Global Stocktake every 5 years (starting in 2023) will assess progress and adjust commitments towards the Paris Accord.     *How will emission commitments be related to concentration requirements?*



# From emissions to concentrations—and back again



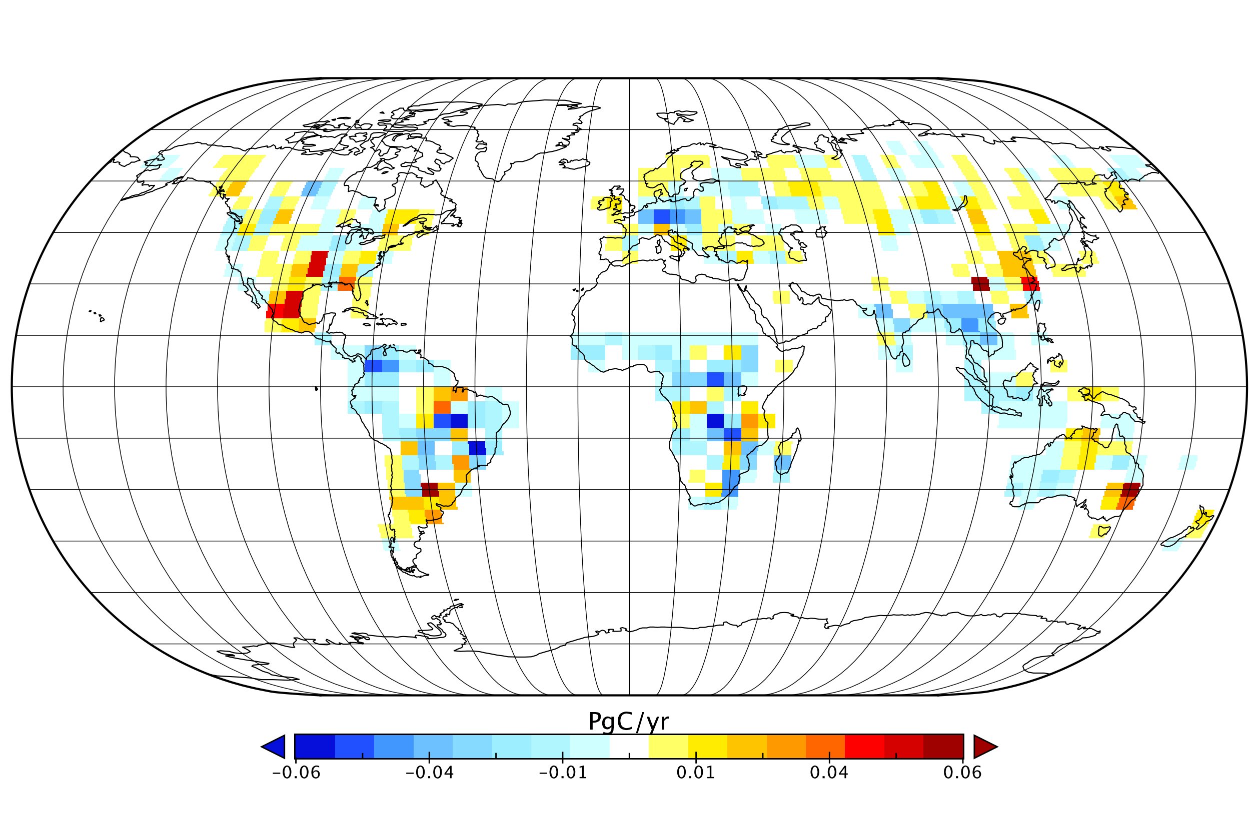

A CONSTELLATION ARCHITECTURE FOR MONITORING CARBON DIOXIDE AND METHANE FROM SPACE, Crisp et al, 2018


How well can we resolve fluxes given concentrations?

# Triumvariate solution: What do you know?

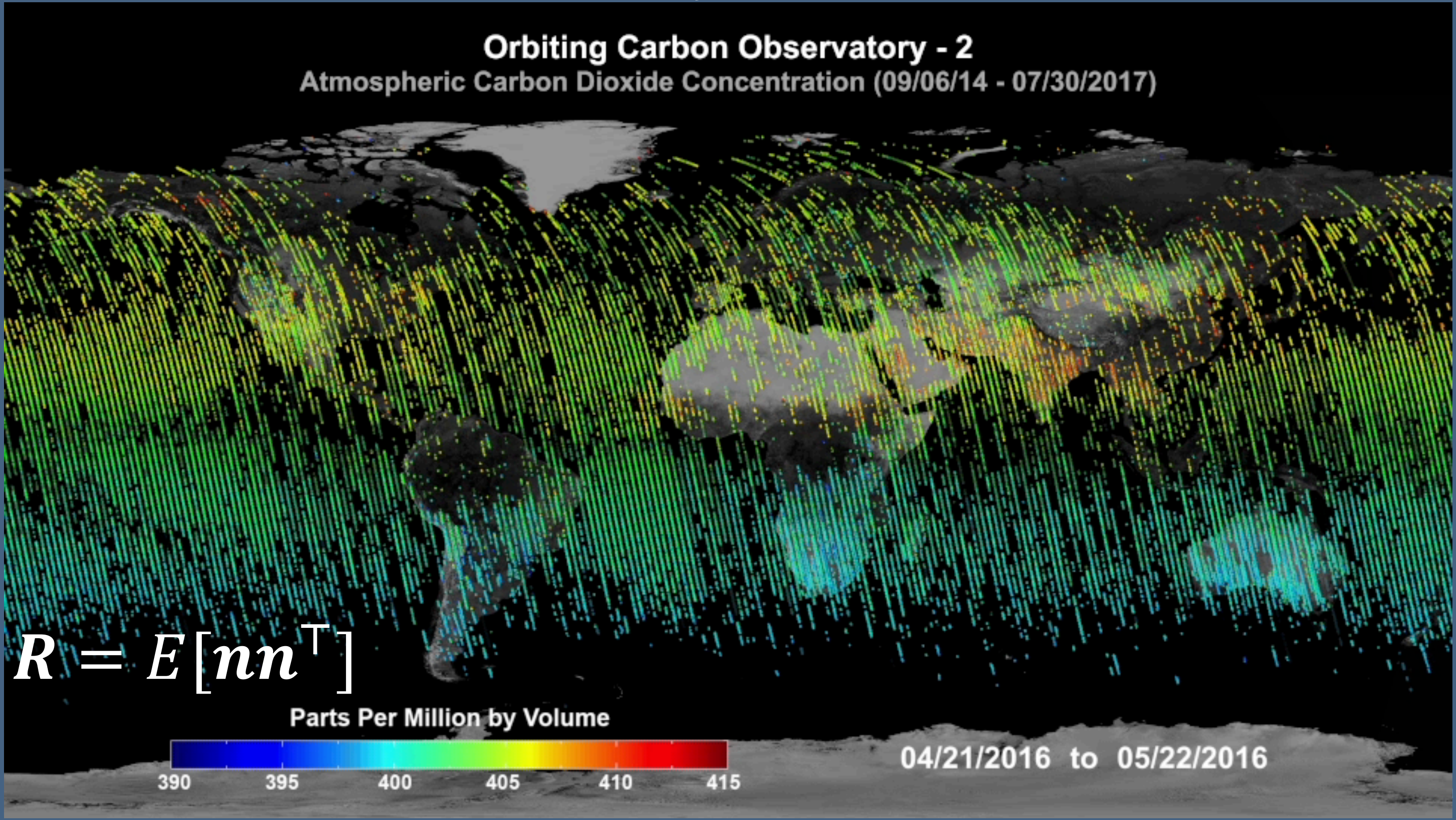
CMS-Flux total flux difference 2011-2010

$$B = E[xx^{\top}]$$




Bowman *et al*, *Earth and Space Sci.* , 2017

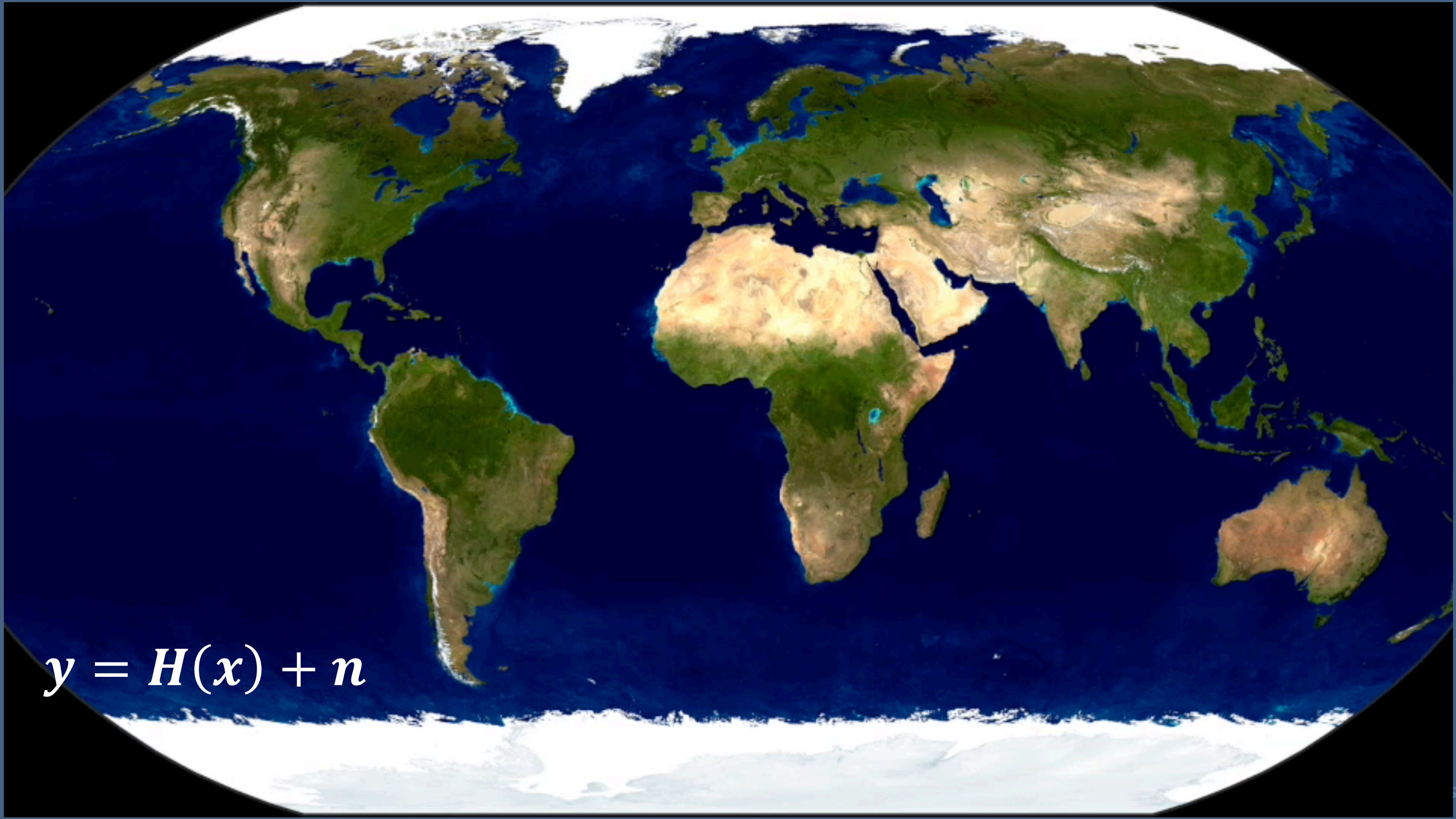
# Triumvariate solution: What do you observe?




$$R = E[nn^{\top}]$$

sa.gov

# From what we observe to what we want to know: Transport



$$y = H(x) + n$$

GEOS-Chem High Performance, C360

Courtesy, Sebastian Eastham, MIT

# The Triumvirate solution

The linear inverse problem can be completely characterized by the observing system, transport, and flux uncertainty (Rodgers, 2000, Tarantola, 2005, Bousserez and Henze, 2015)

$$\mathbf{B}^{1/2}\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H}\mathbf{B}^{1/2} = \sum_i^p \lambda_i \mathbf{v}_i \mathbf{v}_i^T$$

Characterization

Spantini et a, 2015 and Bousserez and Henze, 2018 showed how to choose the optimal k<<p.

*But how to compute?*

$$\mathbf{A} = \frac{\partial \mathbf{x}_a}{\partial \mathbf{x}_{\text{true}}} = \mathbf{B}^{1/2}\left(\sum_{i=1}^{k} \frac{\lambda_i}{(1+\lambda_i)} \mathbf{v}_i \mathbf{v}_i^\top\right)\mathbf{B}^{-1/2}$$

Fast Randomized Optimal Approach for Diagnostic and Optimization (FRODO) computes the SVs ***efficiently*** (asynchronous parallelization) using new probabilistic algorithms for matrix decomposition (Bousserez and Henze, 2018, Halko et al, 2011).

# OSSE Case: OCO-2, 2015

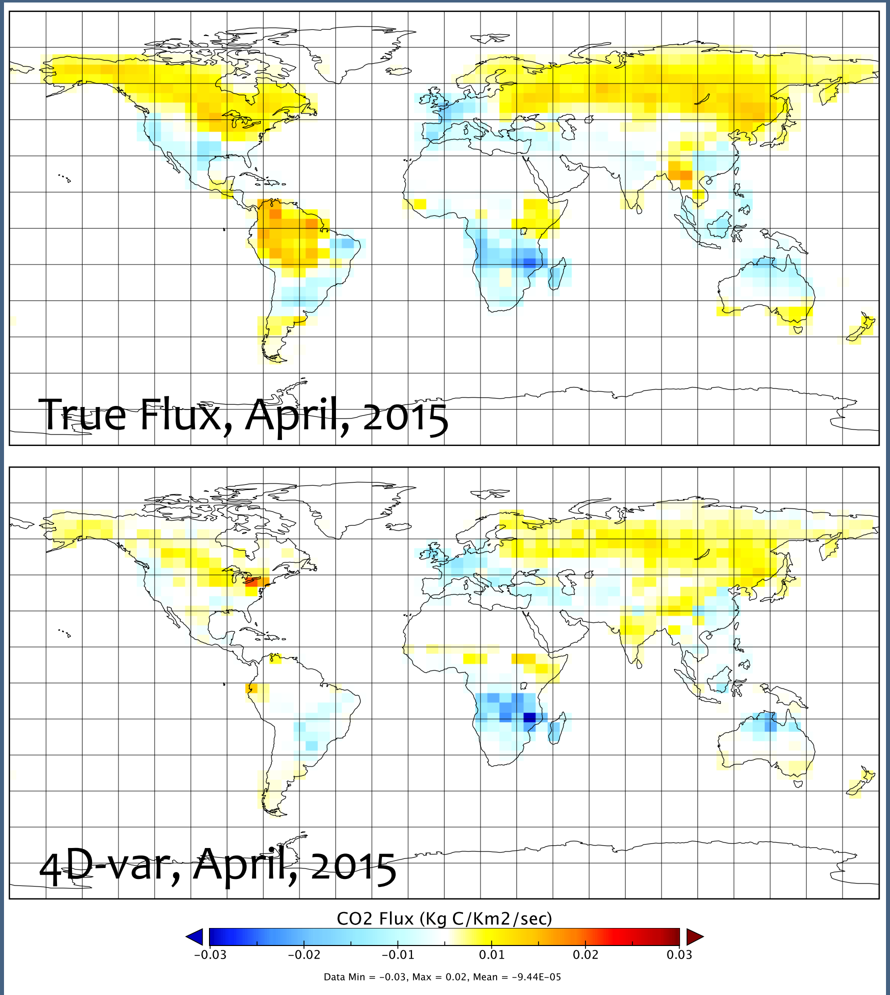
Flux estimates are computed for
land using FRODO using 500 ensembles.

The "true" follow the priori fluxes Liu et al, 2017 and Bowman et al, 2017.

The "prior" fluxes use CARDAMOM (Bloom et al, 2016)

Flux uncertainty is simply 0.5.

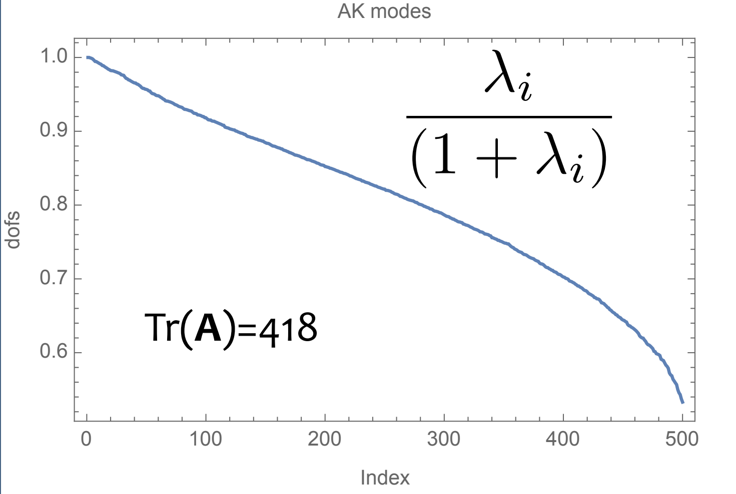
What patterns are controlled?



# The Averaging Kernel and the axes of variation

The averaging kernel (AK) describes the resolvable modes of variability

The degrees of freedom for signal (dofs) is a measure of the independent pieces of information in the inversion.




$$\frac{\lambda_i}{(1+\lambda_i)}$$

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{A}(\mathbf{x} - \mathbf{x}_b) + \epsilon$$

$$\mathbf{A} = \frac{\partial \mathbf{x}_a}{\partial \mathbf{x}_{\mathrm{true}}} = \mathbf{B}^{1/2} \left( \sum_{i=1}^{k} \frac{\lambda_i}{(1+\lambda_i)} \mathbf{v}_i \mathbf{v}_i^{\top} \right) \mathbf{B}^{-1/2}$$

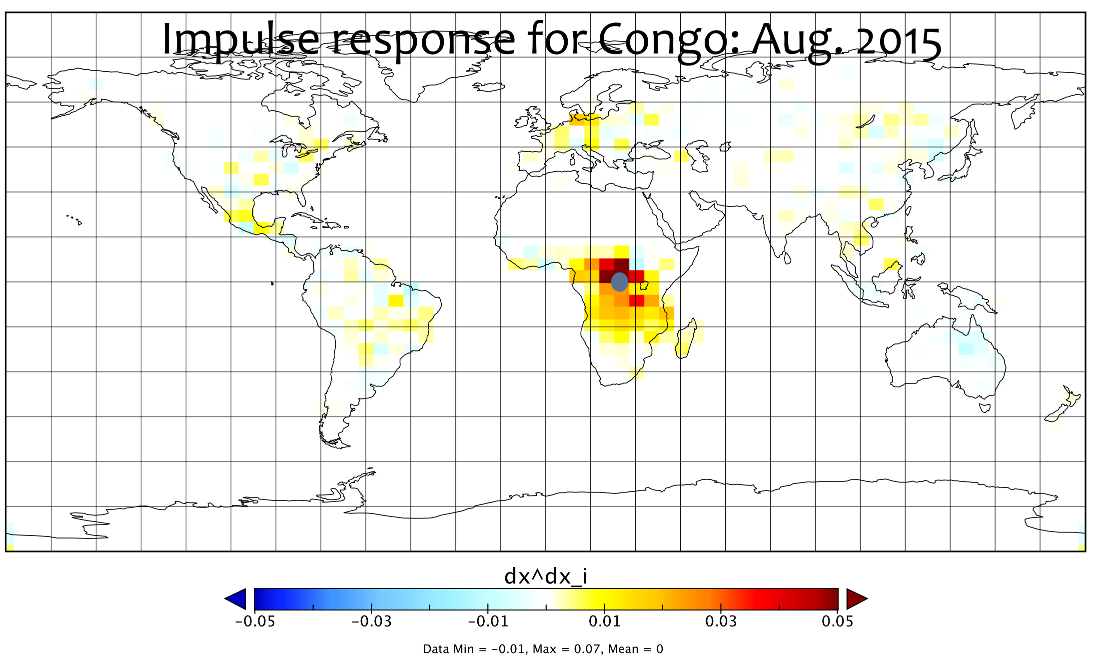
OCO-2 can resolve 418 independent modes.
What about specific locations?

# Flux resolution: Impulse response

The impulse response (IR) is the change in the flux estimate from the change in the actual fluxes at a particular grid box.

The IR is the column of the AK:

$$\mathbf{a}_i = \mathbf{A}\delta_i$$




Congo is a particularly interesting region in the carbon cycle. We'll choose one grid box: (0, 25E)

A change in the true flux at this one grid box in Aug., changes the estimate anisotropically over a roughly 15 ° x15° region.

# How well can OCO-2 resolve fluxes in time?

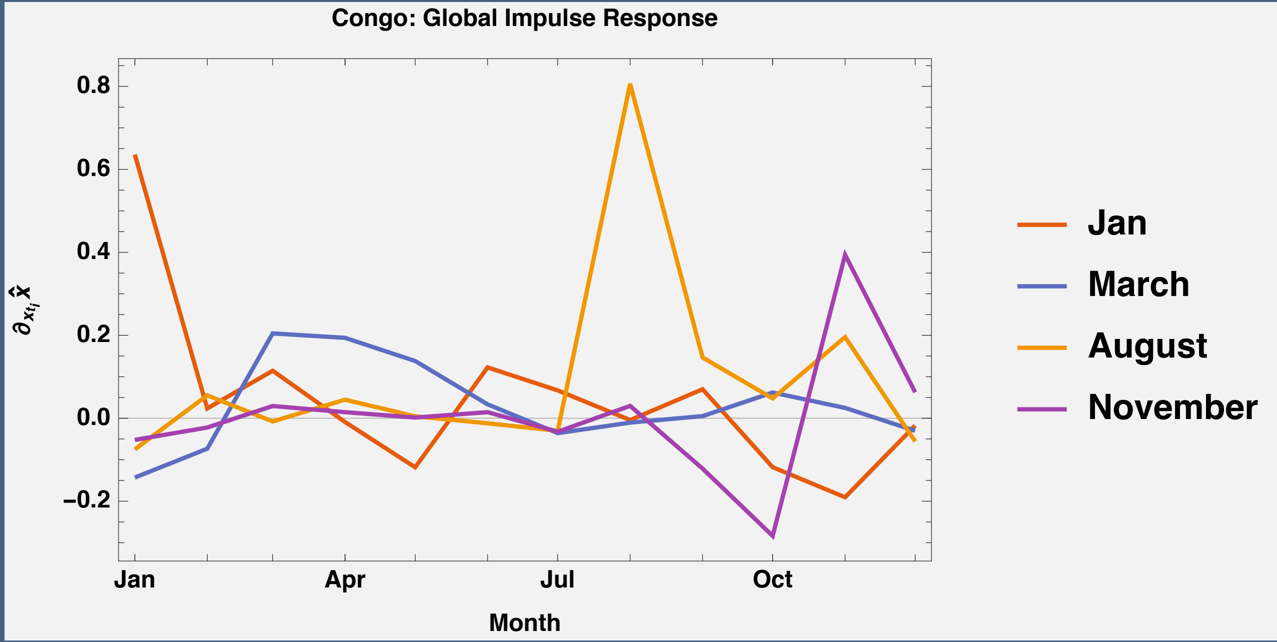
Integrate the Congo IR globally for each month.

January is well resolved but has non-negligible impacts of the following months.

March is poorly resolved and is strongly correlated with April and May, 2015.

August is well resolved.

November is negatively correlated with Oct.



# Conclusions/Future Directions

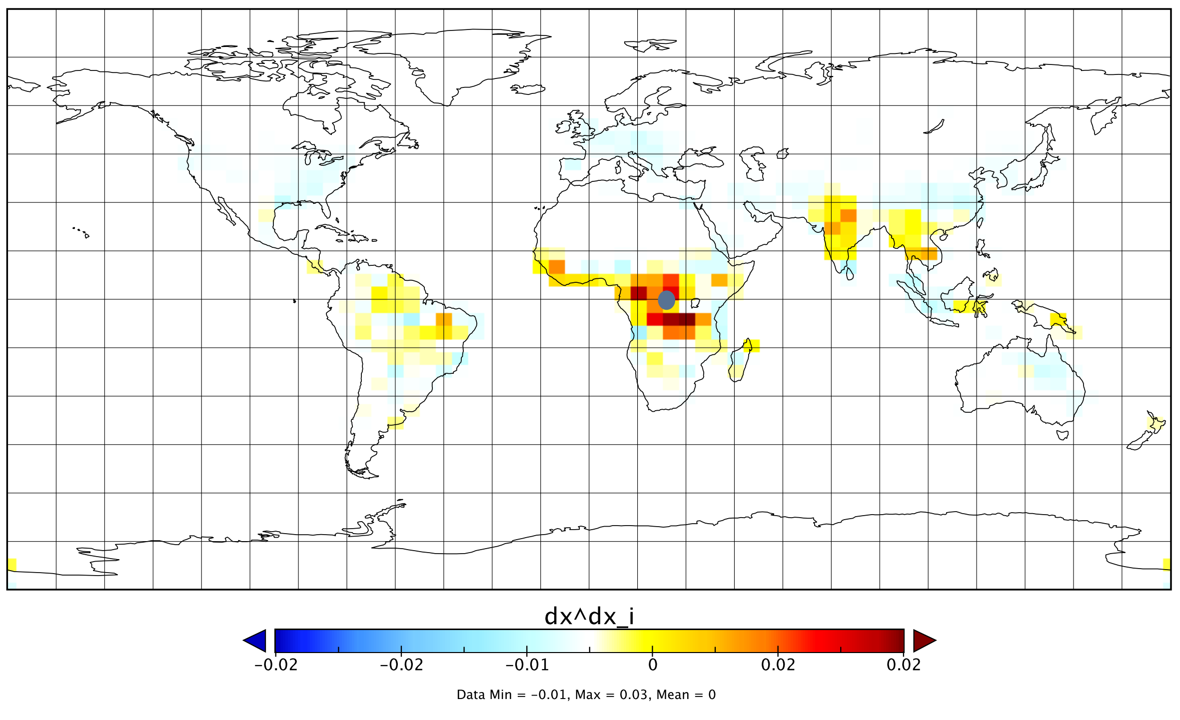
- The ability of carbon monitoring systems to support the global stocktake critically depend on their ability to resolve fluxes given concentrations.
- Application to CMS-Flux constrained by OCO-2 shows that OCO-2 can constrain ~420 independent modes (in the absence systematic errors) over a year.
- Impulse response analysis reveals that the resolution of the inversion is a complex function of space and time.
  - In Africa, IR analysis suggests a resolution of roughly 15 ° x15° , but poor temporal resolution in Spring.
- FRODO enables a rigorous comparison between in-situ, satellites, and constellations.
- Information analysis can now be applied to carbon OSSE.

# Shifting response: March, 2015

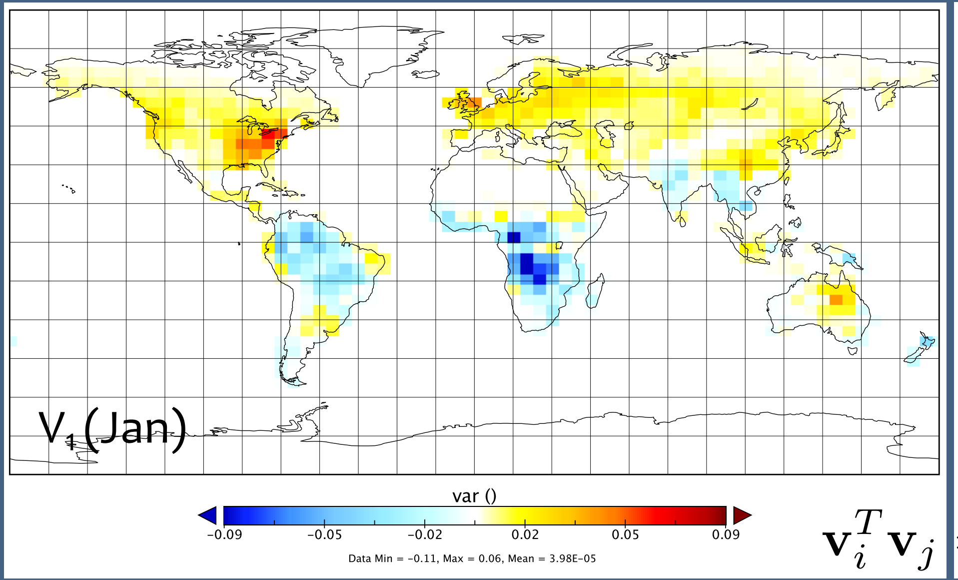
The impulse response (IR) magnitude for March is about ¼ of the August IR.

The Congo IR effects fluxes in non-local continents.

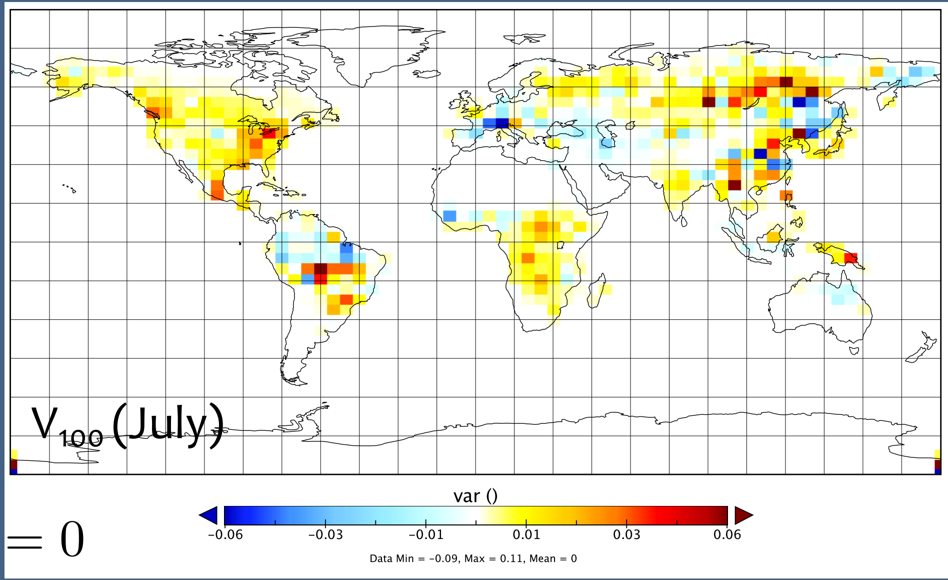
These non-local effects represent transport pathways.



# A spectral approach: patterns of change




$$\mathbf{v}_i^T \mathbf{v}_j = 0$$




The 4D-var solution can approximated as a weighted sum of orthogonal patterns.The weights come from innovations and singular values. The patterns come from transport, observing system, flux uncertainty.

$$\delta \mathbf{z}_a = \sum_{i=1}^{k} \alpha_i \mathbf{v}_i$$

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov